

Comparison Between Continuously Cast and Sand Cast Zinc-Aluminum Alloys Used in Bearing Applications

J. Masounave and G. Huard

Abstract

Tests were carried out using a full size bearing laboratory test rig which simulates typical operating conditions of speed and load. Continuously cast and sand cast zinc-aluminum alloys containing 12% Al (ZA12) and 27% Al (ZA27) were investigated and compared with SAE660 bronze. Stribeck curves as well as load capacity curves (P-V curves) were used to evaluate the performance of the materials. The results showed the sand cast ZA27 alloy as being the material with the best overall performance, followed by the sand cast ZA12 and the continuously cast alloys. Bronze exhibit a behaviour comparable to the ZA27 alloy. Examination of SEM micrographs and a semi-quantitative analysis allow the proposition of a possible wear mechanism for bearings used in conditions of high wear.

BRONZE ALLOYS ARE WIDELY USED as bearing materials because of their good anti-friction properties. The high copper content of these alloys is however responsible for their relatively high cost and high weight. Since about ten years, several research programs have been conducted in order to develop alloys which would improve these two aspects. Earlier studies [1-6] have proved the zinc-aluminum alloys, particularly ZA27, to be possible replacement bearing materials.

Results coming from a joint research program between the Industrial Materials Research Institute, Boucherville, Canada, and the Noranda Research Center, Pointe-Claire, Canada, have shown that a bearing made of continuously cast ZA27, working with a 1144 steel hard shaft (40-45 HR_C), exhibits a performance at least as good as that of a traditional C660 bronze bearing working in the same overall conditions [4]. Parallel to this, short test experiments using a

block-on-ring test apparatus carried out by the Noranda Research Center together with Amax Materials Research Center of Ann Arbor, Michigan have lead to similar conclusions about the continuously cast ZA27 [5]. With this type of test, the sand cast ZA27 alloy exhibited the best overall wear performance, being slightly better than the cast aluminum-bronze C95200 alloy. The authors also concluded that the sand cast test pieces were, in general, better than those fabricated by other casting processes (continuous casting, die casting, permanent mold casting).

The tests carried out in the IMRI laboratories lasted between 200 and 300 hours, and it was shown that severe wear could arise after a period of more than 100 hours in the low wear regime [4]. Such a behaviour may have consequences on the evaluation and ranking of materials using short duration tests during which the bearing would always operate in low wear regime. Long duration tests with sand cast full size bearing appeared therefore interesting to perform, in view to compare their performance with that of continuously cast bearings. Results of such comparative tests are reported here.

EXPERIMENTAL METHOD

TEST RIG - The apparatus used to conduct the wear tests was built at the Industrial Materials Research Institute. Eight full size bearings can be tested simultaneously, although independently, under conditions encountered in real life applications. A schematic diagram of one test station is shown on Figure 1. Each station includes one AISI 1144 steel shaft maintained between two pillow blocks and rotating inside the bearing to be tested. Previous studies [4,6] have shown that the use of a hard steel shaft (40-45 HR_C) instead of a soft one (20-25 HR_C) gives generally a better wear resistance of the journal bearings. This high shaft hardness

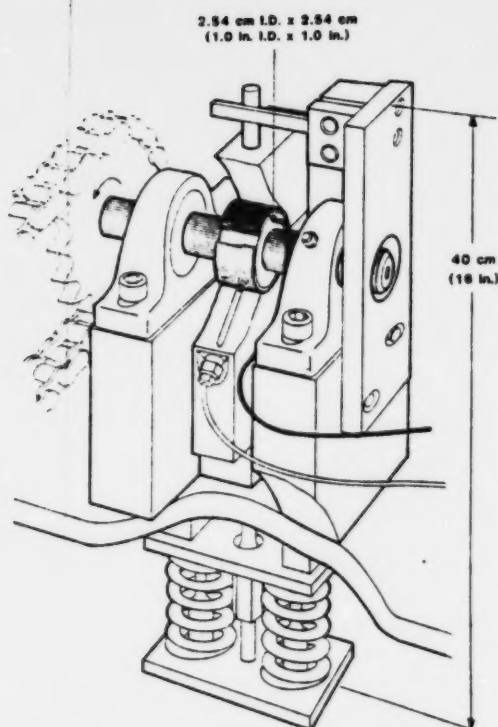


Fig. 1 - Diagram of a single test station for full size bearing wear testing.

was therefore retained for the present study. Also, a shaft roughness of 0.4-0.6 μm CLA was chosen because it is a normal value for shaft operating in real life conditions. The bearing dimensions are 4.42 cm O.D., 2.54 cm I.D. and 2.54 cm length. The diameter clearance is 0.0508 mm and the surface finish, 1.6 μm CLA. Load and speed can be varied while the temperature and the friction force are monitored during the test using a microcomputer. The load is applied on the bearing by means of coiled springs. The stress range, measured with a load cell, goes from 3 to 35 MPa. The shaft speed is controlled by a continuous motion motor and monitored using a stroboscopic light. The speed interval is comprised between 2 and 30 cm/s. The temperature reading uses a thermocouple placed 3 mm below the bearing inside surface. A commercial grease (Sunoco Prestige 741EP) was employed as lubricant. In this choice, no considerations of grease optimization was made, but rather the use of a grease which is currently used for industrial applications. It was supplied automatically to each bearing at a rate of 0.1 mg after each 15 minutes of running time. Each test starts with a run-in period of 6 hours under a load of 3.45 MPa at the speed later considered for the real test.

The wear rate of a bearing is determined by its diameter change divided by the total

distance traveled by the surface of the shaft. Wear values may be classified into three main regimes. Hydrodynamic lubrication occurs when the bearing experiences no or very low measurable wear. Oppositely, the boundary lubrication occurs when at least one of the following three conditions is achieved: the friction coefficient is equal to or higher than 0.1, the temperature of the bearing as measured by the thermocouple exceeds 120°C or the quantity of wear is equal to or higher than $8 \cdot 10^{-9}$ cm/m ($50 \cdot 10^{-9}$ po/pi.). Other cases constitute the region of moderate wear or mixed lubrication.

MATERIALS - Two zinc-aluminum alloys were tested, namely ZA12 and ZA27, the composition of which are given in Table 1. Two fabrication processes were investigated: continuous casting and sand casting. The resulting microstructures essentially consist of primary aluminum-rich dendrites surrounded by an eutectic phase. The sand cast alloys exhibit a coarser microstructure due to their slower cooling rate.

Table 1 - Composition (w%) of the ZA12 and ZA27 alloys (ASTM B669-84)

	Al	Cu	Mg
ZA12	10.5-11.5	0.5-1.25	0.015-0.03
ZA27	25.0-28.0	2.0-2.5	0.01 -0.02

Impurity limits: 0.004% Pb
0.003% Cd
0.002% Sn
0.075% Fe (ZA12)
0.01% Fe (ZA27)

LOAD CAPACITY CURVES

Load capacity curves, or load-velocity curves, reflect the wear intensity of a given alloy for a particular set of stress and rotation speed. These curves are usually dependent on shaft conditions (roughness, hardness, etc.) which were identical for each test of this series. Figure 2 shows a schematic curve which can be divided into three regions corresponding to the regime of wear encountered by the bearing: hydrodynamic lubrication (Region I), moderate wear (Region II) and high wear (Region III). The load capacity of a bearing/shaft combination is represented by the boundary between the regions of moderate and high wear. A better combination leads to a curve which tends toward higher speeds and loads. From the present results shown in Figure 3, the bearing materials may be classified as following, starting with the best one: sand cast ZA27 and ZA12, continuously cast ZA27 and ZA12.

The area at the region of hydrodynamic lubrication is also of importance since it represents the domain where a bearing can be

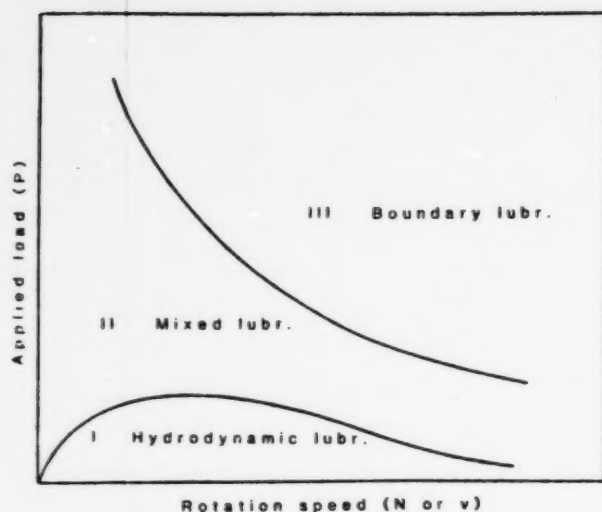


Fig. 2 - Schematic load capacity curve of a bearing.

used with virtually no wear. Having this criteria in mind, the same ranking as previously may be established for the performance of the zinc-aluminum alloys investigated in this study.

STRIECK CURVES - A Stribeck curve is another representation of the behaviour of a bearing assembly which has been widely discussed [7]. It consists of a plot of the friction coefficient as a function of the bearing parameter $\mu N/P$, where μ is the lubricant viscosity, N is the rotation speed and P is the load applied on the bearing. An idealized Stribeck curve is shown on Figure 4. Similarly to load capacity curves, Stribeck curves can be divided into three regions. The right part of the curve (high values of $\mu N/P$) is associated to the hydrodynamic or elastohydrodynamic (EHD) lubrication, and the friction characteristics are determined mostly by the lubricant properties. The low wear rates of this regime

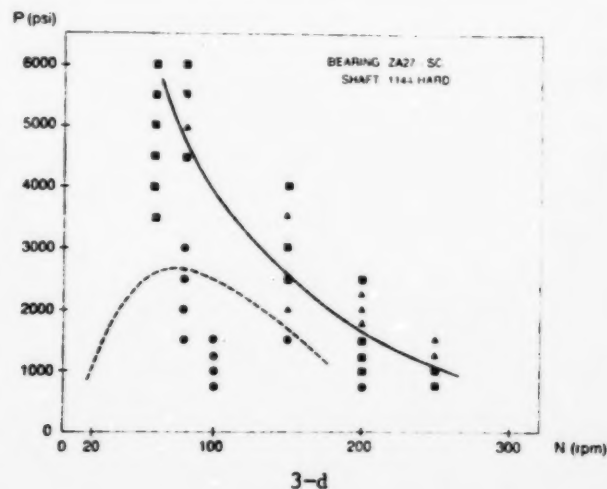
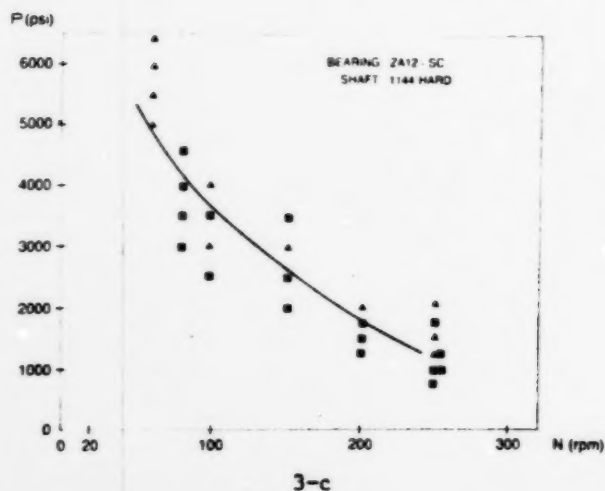
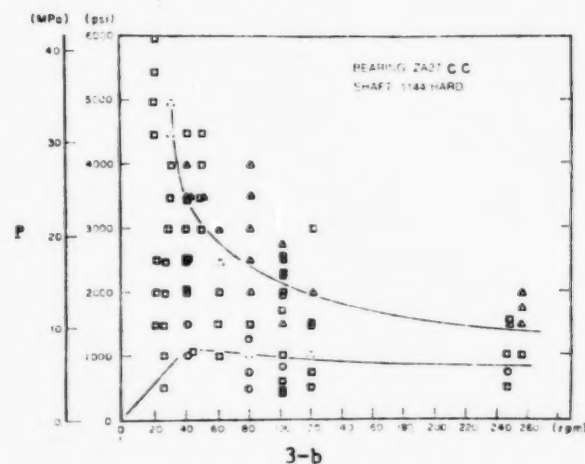
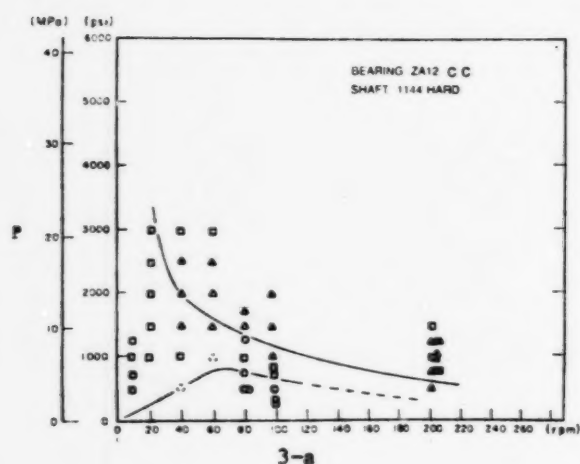


Fig. 3 - Experimental load capacity curves. a) continuously cast ZA12, b) continuously cast ZA27, c) sand cast ZA12, d) sand cast ZA27.

are due to surface fatigue, cavitation wear or surface erosion [7]. The middle part of the Stribeck curve is called the region of mixed

or partial EHD lubrication. The load is now carried by the lubricant and surface asperities because of the low thickness of the lubricant film. The lower the bearing parameter gets, the higher the number of contacting asperities and the friction coefficient are. The bearing is now working in the left part of the Stribeck curve, where the friction and the wear rate are the highest.

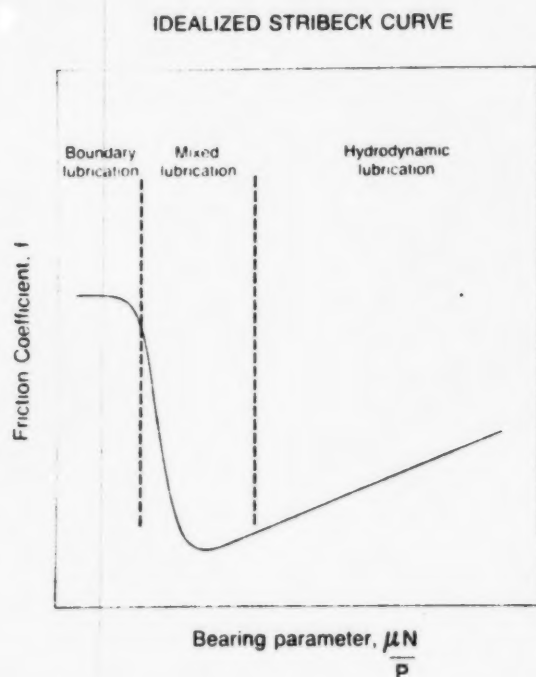


Fig. 4 - Schematic Stribeck curve for a bearing.

From a practical point of view, it is desirable to maintain the friction coefficient as low as possible when the load is increased on the bearing or the speed is decreased. On the Stribeck curve, this is reflected by a minimum point closer to the origine (low friction, low bearing parameter).

The performance of a bearing assembly may therefore be classified after the location of the minimum friction value of its Stribeck curve. From our results (Figure 5) the sand cast ZA27 alloy presents the best performance. It is also to be noted that the experimental scatter band of the sand cast ZA27 in the region of hydrodynamic lubrication is the narrowest of the present study. The other three zinc-aluminum alloys may be ranked roughly in the following order: sand cast ZA12, continuously cast ZA27 and continuously cast ZA12. The Stribeck curve of the C660 bronze is given for comparison in Figure 5e. Its minimum value is comparable to the one obtained with the sand cast ZA27 but the scatter band is larger, with the upper limit

at higher values of friction coefficient. This indicates that the ZA27 alloy should perform a little better than C660 bronze in real bearing applications.

DISCUSSION

As mentioned earlier, the location of the limit between the regions of mixed and boundary lubrication on a P-V graph is an indication of the wear resistance of a material in condition of bearing application. Since this criterion constitutes a valuable way of comparing different materials, the curves obtained for the zinc-aluminum alloys here investigated were replotted on a log-log scale paper (Fig. 6). On this figure, P_c is written for the transition load between the two mentioned regimes while N represents the shaft speed. It can be first noted that the slope of these plots remains basically constant with no regards to the nature of the bearing materials. Other data coming from earlier studies [4,6] were added on this figure in order to show that this observation remains true for a variety of zinc-aluminum alloys investigated in various conditions of shaft hardness and roughness. Since each line drawn on Figure 6 constitutes the boundary between moderate and high wear rates, the wear rate along each of them may be considered as constant.

We can therefore write:

$$P = k' \cdot v^{-0.7} \quad \text{or} \quad k' = P \cdot v^{0.7} \quad (1)$$

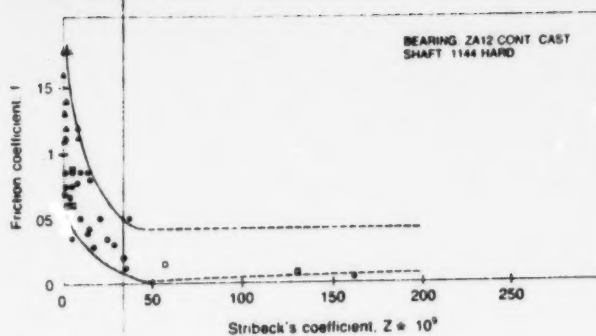
where k' is a constant related to the wear rate at the transition between the regimes of mixed and boundary lubrication.

Also, the ranking of materials may be established when one considers the relative position of the plots which are directly related to the curves given in Figure 3. It also corresponds to the observations of the Stribeck's curves and leads to the same ranking of these zinc-aluminum bearing materials.

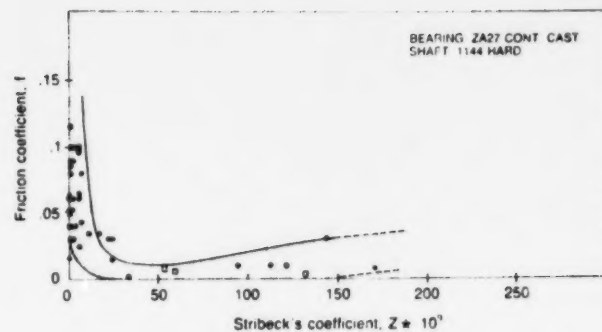
The Archard's equation

$$\Delta V = k \frac{P}{H} S \quad (2)$$

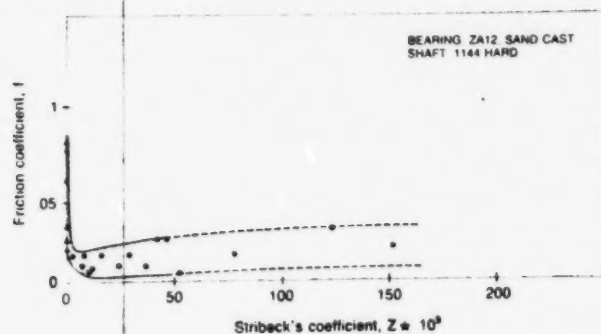
relating the wear volume (ΔV) to the applied load (P), abrasion length (S) and material hardness (H) cannot be used directly to evaluate the wear rate of a journal bearing since it describes abrasion mechanisms which are virtually absent of this case. Furthermore, the effect of speed is not considered in this equation, and Figure 3 shows that the wear resistance of a bearing at a given load varies greatly with the rotation speed. Therefore, the equation (2) has to be modified in order to take the actual wear mechanism into account.



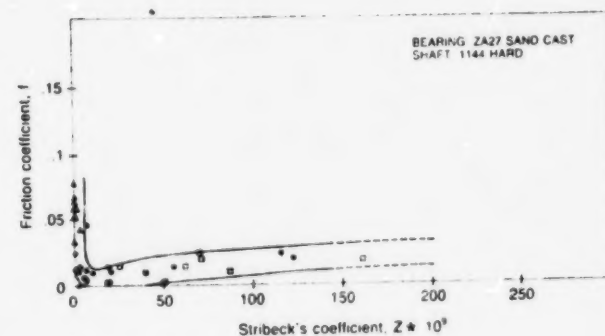
5-a



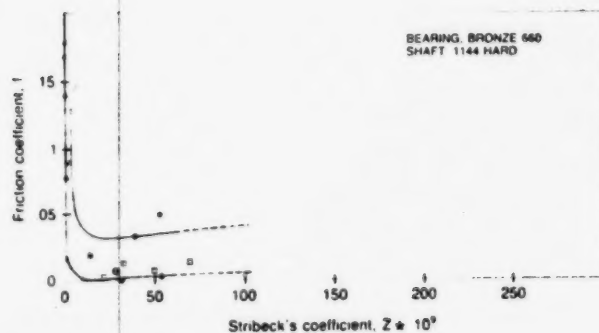
5-b



5-c



5-d



5-e

Fig. 5 - Experimental Stribeck curves. a) continuously cast ZA12, b) continuously cast ZA27, c) sand cast ZA12, d) sand cast ZA27, e) C660 bronze.

Figure 7 shows typical views of a zinc-aluminum alloy submitted to conditions of severe wear. It is seen that the material of the near-surface region experiences a thorough mechanical mixing to an extent at which it becomes impossible to recognize its initial microstructure. The analysis of concentration for aluminum, copper and iron also shows the occurrence of a strong diffusion (Fig. 8). The

presence of iron on the bearing surface confirms that material transfer occurs from the steel shaft to the bearing. Observations were also made of zinc-aluminum particles transferred to the surface of the steel shaft.

In order to establish a semi-quantitative explanation of the wear mechanism arising in these conditions, the following assumptions can be made. Since the microcracks usually initiate inside or just below the heavily deformed surface layer (Figure 7), the wear resistance of bearings operating in conditions of high wear rates is influenced by the properties of this layer. Because the high rates of deformation, it is possible to associate the behaviour of the deformed layer to that of a semi-liquid metals with a high solid fraction. Experiments on the rheology of the semi-liquid metals showed that they have a viscosity (η) related to the shear rate ($\dot{\gamma}$) as per the following relation:

$$\eta \propto \dot{\gamma}^{-n}$$

where n is a constant [8,9]. In the present case, the shear rate may be replaced by the rotation speed of the bearing, so that in the surface layer:

$$\eta \propto v^{-n} \quad (3)$$

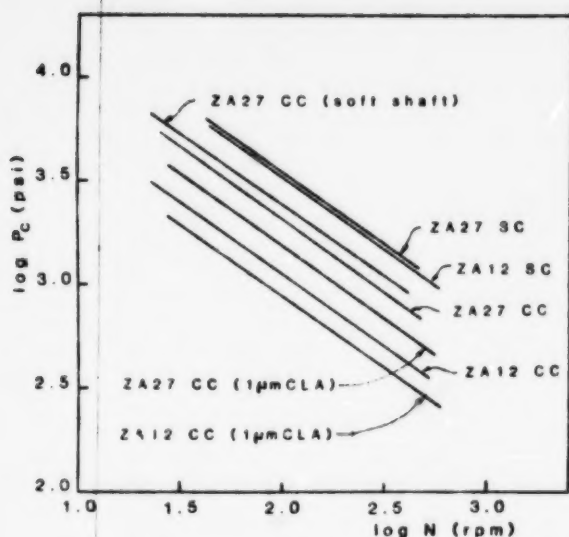


Fig. 6 - Relation between the rotation speed of a bearing and the critical load at the transition between mixed and boundary lubrication.

Furthermore, we may assume the time (t_f) needed to form a particle to be proportional to the viscosity of the surface layer, and the volume (V_p) of this particle to be inversely proportional to the viscosity.

$$t_f \propto \mu \longrightarrow t_f \propto \nu^{-n} \quad (4)$$

$$V_p \propto \mu^{-1} \longrightarrow V_p \propto \nu^n \quad (5)$$

In other words, the higher the rotation speed is, the lower the surface viscosity is. This lower viscosity would be responsible for the production of larger wear particles taking a shorter time to be formed.

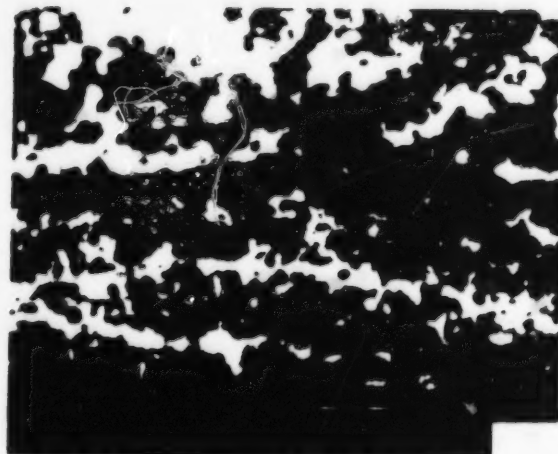
Considering that the total wear volume is roughly proportional to the volume of a single wear particle and inversely proportional to its time of formation, the following relation may be written:

$$\Delta V \propto \frac{P}{H} \cdot V_p \cdot \frac{t}{t_f} \quad (6)$$

where t is the total time of the test. It is to be noted that even if the hardness value H has been included in this relation, its real influence remains undetermined and may be less than it is in abrasion. Substituting relations (4) and (5) into (6) and replacing t by S/ν with S written for the total rubbing distance, we have:



7-a



7-b

Fig. 7 - Typical aspects of heavily worn near-surface layer.

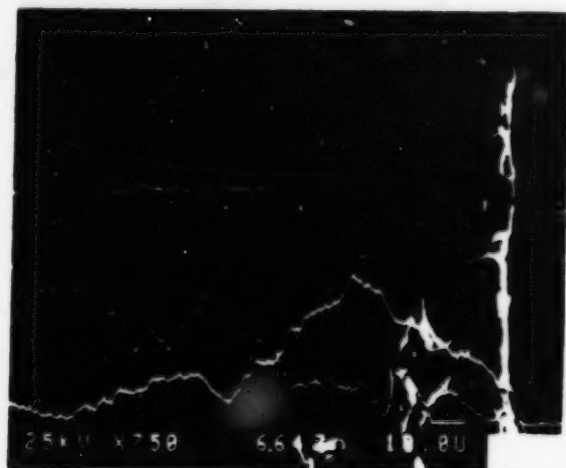


Fig. 8 - Variations of concentration of Fe, Al, Cu at the near-surface layer.

$$\Delta V \propto \frac{P}{H} \cdot \frac{S}{v} \cdot \frac{1}{v^{-n}} \quad (7)$$

$$\Delta V \propto \frac{P}{H} \cdot S \cdot v^{2n-1}$$

This relation is in agreement with the relation (1) coming from the experimental results, since the constant k' of the latter is related to the wear rate. Hence, the exponent of v should be the same in relations (1) and (7), so that:

$$2n-1 = 0.7 \longrightarrow n = 0.85$$

This value of n is in accordance with earlier published data on the rheology of semi-liquid metals [8,9]. This supports the assumption that the metal of the surface layer of a bearing submitted to conditions of high wear behaves like a semi-liquid metal.

CONCLUSIONS

Experimental load capacity curves were used to rank the wear resistance characteristics of some bearing materials. These curves have proved themselves to be very useful for this purpose.

Stribeck's curves of the investigated materials were established and lead to the same ranking as that obtained with the load capacity curves. However, it seems that the latter method gives more accurate results.

Full-size bearing tests were carried out with zinc-aluminum alloys coupled with a steel shaft of 40-45 HRc, and lead to the following ranking of their wear performance: sand cast ZA27, sand cast ZA12, continuously cast ZA27, and continuously cast ZA12. Similar experiments with C660 bronze showed the performance of this alloy to be comparable to that of the sand cast ZA27 alloy.

Examination of the severely worn surface of bearing alloys together with the development of a semi-quantitative model lead to the conclusion that the formation of wear particles involves a thorough mechanical mixing of the surface layer which is more comparable to the rheological behavior of semi-liquid metals with high volume fraction of solid than to usual plastic deformation of metals.

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